PROTON DECAY AND THE PLANCK SCALE*

DANIEL T. LARSON

Theoretical Physics Group, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA

Department of Physics, University of California, Berkeley, CA 94720, USA

Even without grand unification, proton decay can be a powerful probe of physics at the highest energy scales. Supersymmetric theories with conserved R-parity contain Planck-suppressed dimension 5 operators that give important contributions to nucleon decay. These operators are likely controlled by flavor physics, which means current and near future proton decay experiments might yield clues about the fermion mass spectrum. I present a thorough analysis of nucleon partial lifetimes in supersymmetric one-flavon Froggatt-Nielsen models with a single $U(1)_X$ family symmetry which is responsible for the fermionic mass spectrum as well as forbidding R-parity violating interactions. Many of the models naturally lead to nucleon decay near present limits without any reference to grand unification.

1. Two Myths

It is often loosely stated that the observation of proton decay implies the existence of a grand unified theory (GUT). However, it is well known that generic supersymmetric (SUSY) theories possess nonrenormalizable operators that violate baryon- and lepton-number (B and L, respectively). In an effective field theory these operators are necessarily present, and can be dangerous even when suppressed by the Planck scale, $M_{\rm Pl}$ [1].

It is also often sloppily said that R-parity prohibits proton decay in SUSY theories. Though R-parity prohibits the *renormalizable* B- and L-violating operators, it still allows the *nonrenormalizable* superpotential terms $\frac{1}{M}QQQL$ and $\frac{1}{M}\overline{U}\overline{U}\overline{D}\overline{E}$, which contain dimension five operators that can lead to rapid proton decay. In fact, with generic $\mathcal{O}(1)$ coefficients, weak scale squark masses, and $M \sim M_{\rm Pl}$, the proton lifetime comes out to be

*Talk presented at *PASCOS '04*, held at Northeastern University, Boston, MA, August 16-22, 2004. To appear in the Proceedings.

sixteen orders of magnitude below the current experimental limit! This embarrassment has been called SUSY's "dirty little secret".

This "dirty secret" is most likely cleaned up by the physics that generates flavor. If a broken flavor symmetry is the source of the small Yukawa couplings, as in a Froggatt-Nielsen model [2], then that same flavor symmetry will govern the coefficients of the higher dimensional operators mentioned above, allowing the suppression of their coefficients to be predicted.

In what follows we will survey the predictions for nucleon lifetimes as computed in [3] for the class of specific, string-motivated models introduced in [4]. These models are based on a single, anomalous $U(1)_X$ Froggatt-Nielsen flavor symmetry but *do not* require grand unification.

2. Proton Decay Operators

In GUT theories the exchange of X gauge bosons generates B- and L-violating four-fermion operators suppressed by two powers of $M_{\rm GUT}$, yielding the proton decay rate $\Gamma \sim \frac{\alpha_{\rm GUT}^2}{M_{\rm GUT}^4} m_p^5$. For the standard model, $M_{\rm GUT} \sim 10^{15}$ GeV leading to a proton lifetime around 10^{31} years, well below the current limits which now exceed 10^{33} years for many decay modes [5]. In a SUSY-GUT the unification scale is a factor of 10 higher, suppressing the rate from these dimension six operators by four more orders of magnitude, evading the experimental constraint. However, colored Higgs exchange generates dimension five couplings between fermions and their superpartners which lead to four-fermion operators that are suppressed by one power of $M_{\rm GUT}$ and one power of the scalar soft mass, $m_{\rm soft}$. The proton decay rate becomes $\Gamma \sim \frac{\alpha_{\rm GUT}^2}{M_{\rm GUT}^2 m_{\rm soft}^2} m_p^5$. Since we expect $m_{\rm soft} \ll M_{\rm GUT}$, proton decay from these operators is relatively enhanced and very dangerous, excluding the minimal $SU(5)$ SUSY-GUT [6].

Even without grand unification an effective field theory should contain all allowed higher dimensional operators suppressed by $M_{\rm Pl}$, including the dimension-5 B and L violating operators mentioned above. They lead to proton decay with a rate $\Gamma \sim \frac{\alpha^2}{M_{\rm Pl}^2 m_{\rm soft}^2} m_p^5$. If such operators were present with $\mathcal{O}(1)$ coefficients it would be disastrous. Therefore we need to consider the degree to which these coefficients are suppressed by flavor physics.

3. Flavor Model Framework

In the class of models presented in [4] the MSSM superfields are charged under a horizontal $U(1)_X$ symmetry that is spontaneously broken when a

flavon field, A, gets a nonzero VEV generated by string dynamics. Both the MSSM Yukawa terms and the higher dimensional operators are then suppressed by the ratio $\epsilon = \langle A \rangle / M_{\rm Pl}$ raised to the the appropriate power necessary to conserve $U(1)_X$. The string dynamics predicts $\epsilon \sim \sin\theta_C$. The X-charges for the MSSM superfields are restricted by sum rules that ensure anomaly cancellation through the Green-Schwarz mechanism [7], and further constrained by requiring that they lead to the observed fermion mass spectrum and mixings, including neutrinos and the MNS matrix, and by requiring that R-parity be an exact, accidental symmetry of the low energy theory. It is non-trivial that these requirements can be simultaneously fulfilled. There are 24 distinct models with these properties, parametrized by three integers x, y, and z that are related to $\tan\beta$, the CKM texture, and the MNS texture, respectively. (See [4, 3] for details.)

4. Results

The 24 models each make predictions for the parametric size of the coefficients appearing in front of the dimension-five B and L violating operators, allowing us to compute the lifetime of the proton predicted by each model.

There are two types of uncertainties that enter into our predictions. The first type of uncertainty comes from our ignorance of β_p, the overall scale of the matrix elements for proton decay as computed using the chiral Lagrangian technique [8], and our ignorance of the superpartner mass scale $m_{\rm soft}$. These two uncertainties will hopefully be reduced with time. The second type of uncertainty is inherent in our effective field theory framework and comes from the unknown $\mathcal{O}(1)$ coefficients that appear in front of each higher dimensional operator. We estimate the effect of the unknown phases of these coefficients by adding contributing amplitudes either incoherently, destructively, or constructively.

Figure 1 shows the partial lifetimes for the most constraining mode, $p \to K^+\bar{\nu}$, for all 24 models labeled by the parameters x, y, and z. Already many of the models are disfavored, unless they have significant cancellations between contributing amplitudes. The models that are least constrained are those with lower $\tan\beta$ (higher x). However, the uncertainties in β_p and $m_{\rm soft}$ can potentially change the overall scale of the prediction by the factors shown graphically to the right of Figure 1.

For the proton the next modes to appear after $p \to K^+\bar{\nu}$ are generally $p \to \pi^0 e^+$, $p \to \pi^0\mu^+$, and $p \to K^0\mu^+$. In Figure 2 we show the expected lifetime for those four modes in the 12 models with $\tan\beta \lesssim 10$. We see

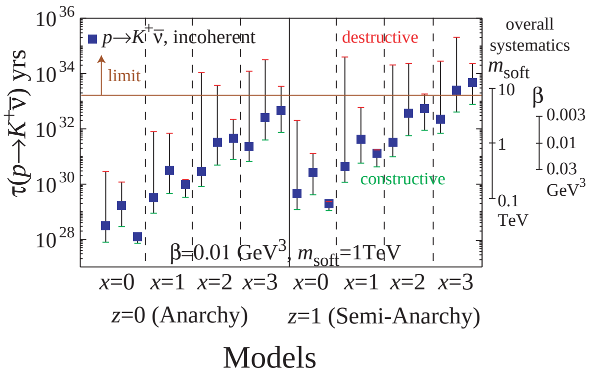

Figure 1. Plot of proton partial lifetime in years for the mode $p \to K^+\bar{\nu}$. Within each half $\tan\beta$ decreases from left to right. The error bars are *not* 1σ bars, but show the shift from incoherent addition of amplitudes (central value) due to destructive and constructive interference. The horizontal line shows the experimental lower limit of 1.6×10^{33} years. The scales on the right show the overall shift caused by changing either m_{soft} or β_p away from $m_{\text{soft}} = 1$ and $\beta_p = 0.01$.

that most models which survive the constraint from $p \to K^+\bar{\nu}$ have a lifetime for $p \to \pi^0\mu^+$ that is within two or three orders of magnitude of the experimental bound, while $p \to K^0\mu^+$ is only slightly larger, and $p \to \pi^0 e^+$ can potentially be smaller. This raises the exciting possibility of two or three decay modes being detected in the coming round of experiments.

Figure 3 shows the partial lifetimes in 11 proton and neutron decay modes for three models, illustrating how various modes can discriminate between models. For example, any mode involving a muon in the final state can differentiate Model 1 from Models 2 and 3.

5. Conclusion

Focusing on a class of string motivated Froggatt-Nielsen models that explain the masses and mixings of all SM fermions while automatically enforcing R-parity, we have shown that nucleon decay is a powerful probe of Planck scale physics. In these models Planck suppressed operators lead to nucleon lifetimes that are generically right near the current experimental limits, even without grand unification. Since current bounds constrain many of the 24 models of this type, we conclude that proton decay is already probing physics at the Planck scale.

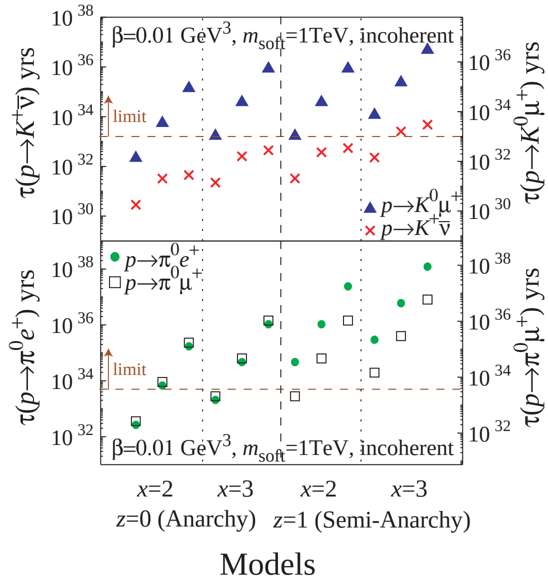

Figure 2. Comparison of proton lifetime in years for four different decay modes. The upper plot shows the computed lifetime for $p \to K^+ \bar{\nu}$ (×, left axis) and $p \to K^0 \mu^+$ (▲, right axis). The lower plot shows $p \to \pi^0 e^+$ (•, left axis) and $p \to \pi^0 \mu^+$ (□, right axis).

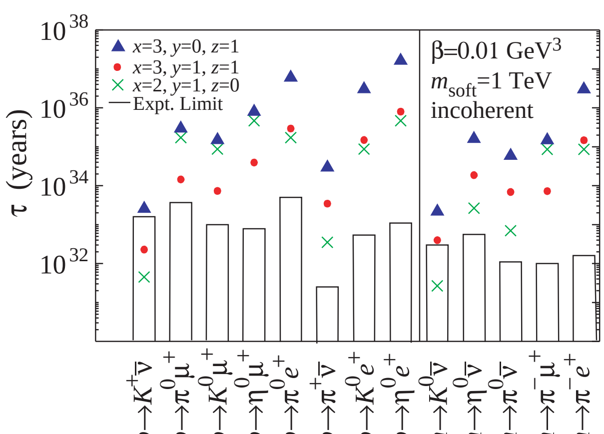

Figure 3. Plot of nucleon lifetime in years for eight proton decay modes (left side) and five neutron decay modes (right side). The different symbols represent different $U(1)_X$ charge assignments. The experimental limit for each mode is shown as a vertical column.

Acknowledgments

DTL thanks R. Harnik, H. Murayama, and M. Thormeier for fruitful collaboration. This work was supported in part by the DOE under contract DE-AC03-76SF00098 and in part by NSF grant PHY-0098840.

References

1. H. Murayama and D. B. Kaplan, Phys. Lett. B **336**, 221 (1994) [arXiv:hep-ph/9406423].
2. C. D. Froggatt and H. B. Nielsen, Nucl. Phys. B **147**, 277 (1979).
3. R. Harnik, D. T. Larson, H. Murayama and M. Thormeier, arXiv:hep-ph/0404260.
4. H. K. Dreiner, H. Murayama and M. Thormeier, arXiv:hep-ph/0312012.
5. E. Kearns, Talk at Snowmass 2001, http://hep.bu.edu/~kearns/pub/kearns-pdk-snowmass.pdf.
6. H. Murayama and A. Pierce, Phys. Rev. D **65**, 055009 (2002) [arXiv:hep-ph/0108104].
7. M. B. Green and J. H. Schwarz, Phys. Lett. B **149**, 117 (1984).
8. M. Claudson, M. B. Wise and L. J. Hall, Nucl. Phys. B **195**, 297 (1982).